Detailed stellar populations of dwarf elliptical galaxies

Sen, Seyda

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1 Introduction

Yaşamak
Bir ağaç gibi tek ve hür
Ve bir orman gibi kardeşçesine.

To live!
Like a tree alone and free
Like a forest in brotherhood.

Nazım Hikmet RAN

1.1 Galaxies: a Brief Introduction

The Milky Way, in which we are resident, is one of many galaxies. As a matter of fact, the Milky Way, also called the Galaxy, is an average member of the class of spiral galaxies.

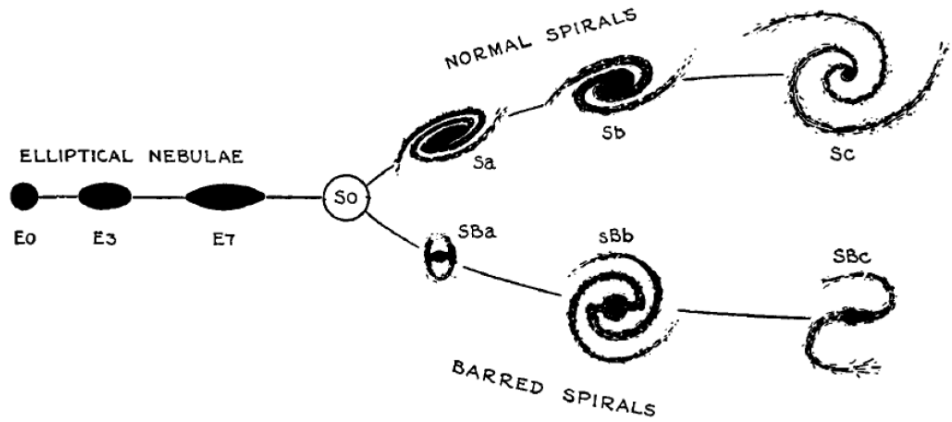
Galaxies are gravitationally bound entities, typically consisting of stars, interstellar matter (gas and dust), stellar remnants (white dwarfs, neutron stars and black holes) and dark matter. These objects, extraordinarily beautiful and diverse whose nature, structure and origin have intrigued astronomers ever since the first galaxy images were taken (without knowing their nature). C. Messier started to catalogue the fuzzy objects which he called nebulae in the mid-eighteen century. Among them M31, the Andromeda galaxy, is listed as 31^{st} objects in the catalog. However, Messier did not determine their nature or distance.

In 1925, Edwin Hubble identified Cepheids in Andromeda. Cepheids, which are pulsating stars, can be used as a distance indicators, because their pulsation period is related directly to their luminosity. He derived the distance of M31 and provided clear evidence that M31 must be extragalactic. His discovery fundamentally changed the view of the Universe, which by then was believed to consist solely of the Milky Way, and opened a new area in astronomy.

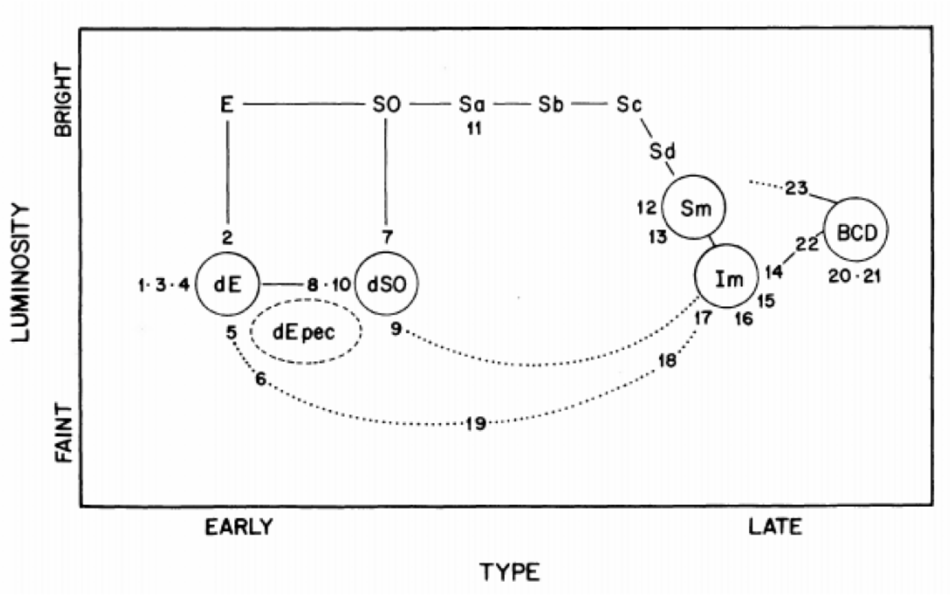
Galaxies are a diverse class of objects, and span a wide range of luminosities, sizes and masses. The classification of objects depends on the type of observations so the first distinctive property of galaxies is their morphology.

Hubble was the first one to classify galaxies according to their morphology in the optical waveband. He introduced a tuning fork diagram according to this, on which three main galaxy types (elliptical, spirals and lenticular) exist. This tuning fork, describing schematically his galaxy classification, is shown in Figure 1.1a.

Ellipticals are divided into subclasses according to their ellipticity (e=1-b/a, with a and b, the semi-major and semi-minor axis, respectively), vary from nearly circular to elongated. Ellipticals are apparently simple smooth, almost featureless systems, contain little cold gas and dust. The class of lenticular (S0) represents the transition between ellipticals and spirals. These galaxies are called lenticulars, because they are lentil-shaped galaxies which are surrounded by a fainter disk without spiral



(a)



(b)

Figure 1.1 – **a**) *Hubble's "Tuning Fork" describing his classification sheme based on their morphological type.* **b**) *The classification system of Sandage & Binggeli (1984) (their Figure 1) showing the different morphological types in the luminosity - morphological type plane, including dwarf galaxies.*

arms. Proceeding further to the right on the tuning fork towards the class of spiral galaxies, we find two subclasses: normal spirals (S' s) and barred spirals (SB' s). Galaxies in each of these subclasses are classified as a function of the brightness ratio of bulge and disk and in increasing importance of the spiral arms, and are identified using the letter sequence a, ab, b, c, cd and d, later m. At the very right we find the irregular galaxies. Irregular galaxies have neither a dominating bulge nor a rotationally symmetric disk and lack any obvious symmetry. Rather, their appearance is generally patchy, dominated by a few HII regions. Hubble did not include this class in his original sequence because he was uncertain whether it should be considered an extension of any of the other classes. Nowadays irregulars are usually included as an extension to the spiral galaxies. Figure 1.1b shows the classification system of Sandage & Binggeli (1984) with the different morphological types in the luminosity morphological type plane.

The galaxies on the left side of the tuning fork are referred to as early-type galaxies, while spirals and irregulars are also called late-type galaxies. Early-type galaxies are mostly made of old stars, without much star formation, with a broad range of kinematical properties (fast to no rotation), and often located in high density environment. On the other side of the tuning fork, spiral galaxies have ongoing star formation, a larger fraction of cold gas, kinematics dominated by rotation, and are found in regions with a lower density of galaxies.

Since Hubble, several classification schemes have been introduced. de Vaucouleurs (1959) revised and expanded the Hubble classification, and put spirals in the Hubble sequence into a sub gradation by adding another class between S0 and Sa (called S0a). When it was known that many irregular galaxies showed weak spirals arms, he extended the sequence with new classes, such as Scd, Sd, Sdm, Sm, Im (where the 'm' refers to Magellanic prototypes).

Present-day galaxies display a wide range of properties so they can be seen as laboratories where the formation and evolution can be investigated.

1.2 Dwarf Galaxy Morphologies

Dwarf galaxies are galaxies with luminosities smaller than 5 10^9 $L_\odot$, corresponding to about M_B = -18. The term dwarf galaxies covers different sub-classes, based on morphology or surface brightness. Many of these classes have only been discovered relatively recently, because of the improved observational capabilities.Their classification scheme is similar to the Hubble classification, with just the prefix 'dwarf' attached: dwarf elliptical, dwarf spiral galaxies, dwarf irregular galaxies. Sometimes the formation of a certain type of galaxy is similar to that of dwarfs of that type, but not always.

- *Dwarf Elliptical Galaxies (dEs):* These galaxies are named 'ellipticals' because of their smooth and elliptical appearance, which is characterized by symmetric isophotes. They have lower surface brightness and a lower metallicity compared to their massive elliptical counterparts. They cover an absolute B-magnitude range between -15 and -18 mag. Dwarf Spheroidals (dSphs) exhibit a still lower luminosity and surface brightness, being fainter than M_B $\sim$ -15. Today, dSph galaxies present the faint end of dEs. Dwarf elipticals, although mostly featureless, do still often have structure, so additional subgroups have been added, like dE(di) to refer to dwarf ellipticals that contain disk-like features like faint spiral arms or bars and dE(bc) for dwarfs with a blue center, dE(N) refers to dwarf ellipticals that have a nuclear star cluster in their center while dE(nN) refers to those that do not have a nuclear cluster (Lisker et al. 2007).

- *Blue Compact Dwarf (BCD):* They are clearly bluer than other dwarfs, even irregular galaxies. BCDs are often categorized as a subclass of dIrr galaxies. They contain an appreciable amount of gas, and generally show high levels of star formation, contrary to dIrrs where stars are forming in a more extended area. Their spectra show strong emission lines and blue continuum.

- *Ultra Compact Dwarf (UCD):* These are the most compact dwarf galaxies with sizes similar to star clusters (R_e $\sim$ 10-50 pc). They are characterized by old stellar populations, are larger, brighter and more massive than the biggest Milky Way globular clusters (GCs), but at the same time significantly more compact than typical dwarf galaxies of comparable luminosity.

- *Ultra Faint Dwarf (UFD):* UFDs appear to be a low luminosity subclass of classical dwarf spheroidals, with low stellar masses, and old, metal-poor stellar populations. The kinematics of these galaxies indicate that they are dominated by dark matter (e.g. Simon & Geha 2007).
- *Tidal Dwarf Galaxies (TDG):* They form from the tidal debris detached from larger galaxies during tidal interactions, are not expected to have much dark matter content but they should have ongoing star formation.

1.3 Dwarf Elliptical Galaxies (dEs)

Dwarf galaxies are low mass and low luminosity systems that have shallow potential wells. They have low surface brightness and exponentially declining radial surface brightness profiles. They are the numerically dominant galaxy class in clusters, by far outnumbering any other type (Binggeli, Sandage & Tammann 1988). Figure 1.2 shows that the luminostiy function of dEs only dominates in cluster environments. They are found in high-density environments and are very rare in isolation (Gavazzi et al. 2010; Geha et al. 2012; Blanton et al. 2005).

If the environment plays an important role in the formation and evolution of galaxies, then dwarfs would be the most affected systems. Within the dwarfs, dwarf early-type galaxies (dEs) are the most common population of galaxies in clusters (Ferguson & Binggeli 1994), thus, they are excellent "laboratories" to test the mechanisms acting in these regions of high density.

The class of dEs contains a large range of internal properties and their structures are very complicated. We know more detail about their substructure which includes disks, sprial arms and irregular features. In a series of papers, Lisker, Grebel & Binggeli (2006); Lisker et al. (2006, 2007) have proposed that the cluster dwarf galaxies population is composed of different sub-categories of objects based on their features, of which not all have been formed in the same way.

It is thought that dE's are spiral or irregular galaxies that have been transformed as they fall into a cluster. There are two main mechanisms

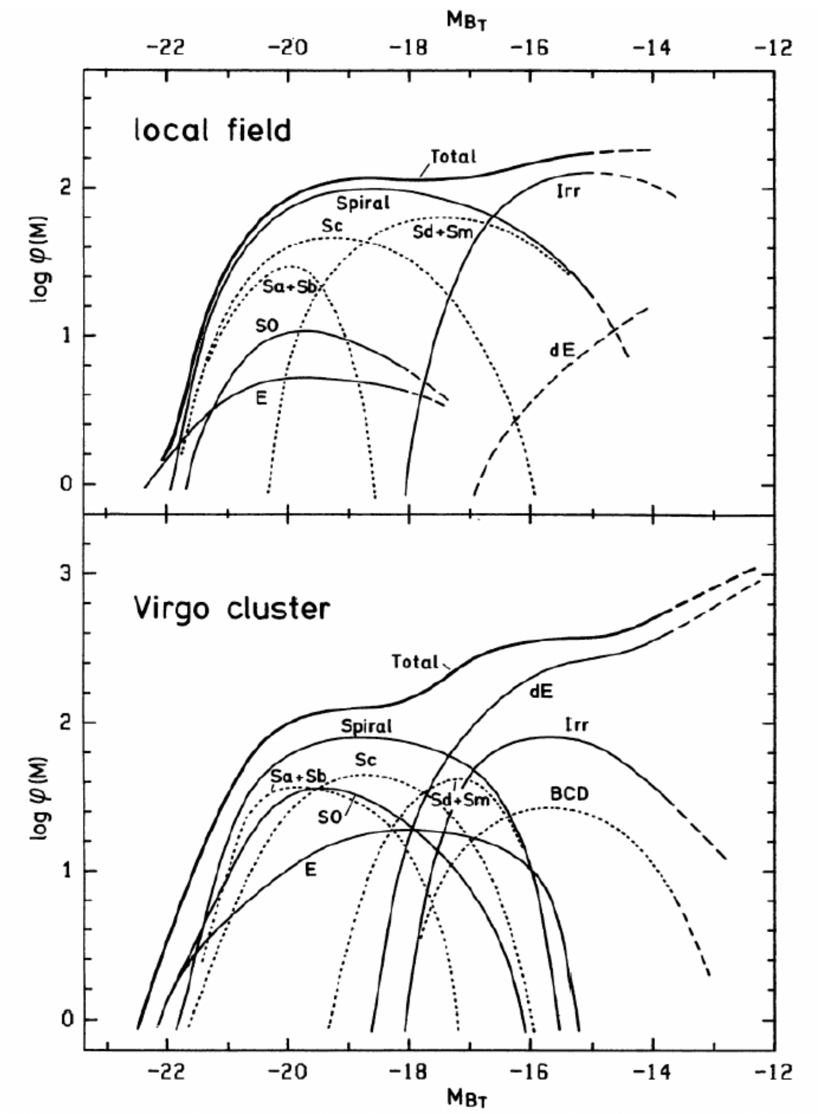


Figure 1.2 – *Luminosity function of galaxies for different Hubble types of field galaxies (top) and galaxies in the Virgo Cluster of galaxies (bottom). From (Binggeli, Sandage & Tammann 1988).*

proposed for this transformation of properties: harassment, i.e. the gravitational interaction between a galaxy and the potential of the cluster, mostly of other galaxies (Moore, Lake & Katz 1998) and ram-pressure stripping (Gunn & Gott 1972; Lin & Faber 1983). In a ram-pressure stripping event the galaxy falling into the cluster loses its gas and rapidly quenches its star formation, strongly depending on the density of the environment, but as this process does not directly affect the stars, their angular momentum should be conserved. On the other hand, galaxy harassment is a significantly more violent process that can remove a large fraction of the stellar mass, change the morphology of the galaxy, and lose a substantially fraction of the angular momentum of the stars so that disks are transformed into more spheroidal objects. For a more detailed review on these effects, see Boselli & Gavazzi (2006, 2014).

1.3.1 Photometry

The fundamental way to study the structure of dwarfs is to use of surface-brightness profiles. This technique of galaxy decomposition and fitting of the light profile give us important clues to understand their scaling relations and morphological transformations of galaxies in cluster environments. The surface-brightness of dwarf early-type galaxies is not fitting either the Hubble's $1/r^2$ (Hubble 1930) or the de Vaucouleurs' law (de Vaucouleurs 1948). Their surface brightness is not similar to that of massive ellipticals. The dE luminosity profiles are good described by exponential profiles; these exponential profiles can be linked to the evolution of spiral-irregular galaxies (Faber & Lin 1983).

A number of analyses have suggested that dwarf ellipticals do not follow the giant elliptical scaling relations, for example the photometric relations (eg., the colour-magnitude relation) appear to show a separation between the two groups (de Vaucouleurs, 1961; Caldwell, 1983). Modern work (Venhola et al. 2019, Roediger et al 2017, Hamraz et al. 2019), however show that giants and dwarfs follow the same relation. The nucleated early-type dwarfs' color-magnitude diagram is different from the non-nucleated ones (Lisker, Grebel & Binggeli, 2008). It shows that their formation could be different from each other.

1.3.2 Spectroscopic Analysis

The kinematics of dwarf galaxies has been studied using slit spectroscopy and Integral Field Unit (IFU) spectroscopy. First of all to determine the kinematic information of dwarf galaxies, we need to obtain high signal-to-noise (S/N) spectroscopic data. For dwarfs it is not easy due to their low surface brightness.

The kinematics of a galaxy is ordered by stellar motion that can either be dominated by rotationally supported motion (disk-like rotation) or by pressure supported (random orbital motions), where the velocity dispersion of a system is measured from the velocity broadening in the spectral lines.

dEs in the nearby clusters show a large range of kinematics, from rotationally supported systems to mostly pressure supported ones (see e.g. Toloba et al. 2011; Ryś, Falcón-Barroso & van de Ven 2013; Toloba et al. 2015).The reason for such a large range is still being debated, and it has to be linked to the different mechanisms involved in their formation and/or environmental factors. Alternatively, the importance of rotation is qualified by the parameter, λ_R, when a binned 2D map of IFU spectroscopic data is available (Emsellem et al. 2007).

Toloba et al. (2015) showed that the slow rotating dEs are mostly located in the inner parts while the fast rotators are found in the outer parts of the Virgo cluster. They showed also that the fast rotators are generally of dE(di) morphological type, and that the fraction of the fast rotators increases with decreasing galaxy surface brightness. These facts can be explained by dwarfs that lost their angular momentum due to the interactions that occur in a dense environment.

Some of the dEs show kinematic anomalies, also called kinematically decoupled cores (KDCs). KDCs could be formed before the dEs progenitors enter a cluster environment where they come together with lower velocity encounters in smaller groups (De Rijcke et al. 2004).

1.4 Dwarf Galaxies in the Cosmological Context

If one wants to study the origin of dwarf galaxies, it is important to also consider the cosmological context. The current view of the Universe relies on the Big Bang which started from a single originating event, and expanded according to the so-called ΛCDM cosmological framework. In this theory, the Universe is homogeneous and isotropic on large scales and is made of cold dark matter (CDM), ordinary matter, neutrinos, photons.

According to the ΛCDM model, only some 4.9% of the total mass density of the Universe contains ordinary matter from which visible planets, stars and galaxies are made. The rest of the matter comprises cold, non-interacting matter, of which only its gravitational force is known. The dark matter (DM) collapses onto dark halos. These dark matter halos become the seeds of galaxies. It is thought that the smallest halos were created first, and more massive halos form from a series of mergers (White & Rees 1978; White & Frenk 1991).

The ΛCDM model is supported by a variety of observational evidence such as the existence and structure (and anisotropies) of the Cosmic Microwave Background (CMB) radiation, the Hubble expansion rate, the large scale structure of the Universe and and the observed distribution of lighter elements (i.e. Hydrogen, Helium, Lithium).

While the Universe expanded, the temperature and density gradually decreased, and after the BigBang in three minutes Hydrogen, Helium etc. were created; these are considered to be primordial elements. When the Universe was around 400 000 years old the temperature and density decreased enough to allow these elements to recombine with electrons and form neutral atoms. This cosmic phase is called as the "epoch of reionization". Over the time all other heavier elements, or metals* are formed by nucleosynthesis in in the interior of stars. What we see in the Universe today is that stellar nucleosynthesis is responsible for the creation of almost all elements. It was first studied in the 1950's by Fowler and Hoyle, culminating in the B2FH (Burbidge, Burbidge, Fowler, & Hoyle 1957) paper.

1.5 Elemental Abundances

1.5.1 The formation of the elements

Stars spend most of their lifetime on the main sequence (MS) where they convert Hydrogen to Helium via the proton-proton chain in low mass stars, and via proton captures by carbon, nitrogen, and oxygen atoms (in the CNO cycles) in more massive stars. Since stars of different masses do not produce the same amount of all elements and also different types of supernova explosions create a different chemical signature, one can determine from the elemental fingerprint of a star in which kind of

* In astronomy all elements which are heavier than helium referred to as "metals"

environment a star was born because the exact chemical composition of a star depends on its birth environment. In addition to this, the metallicity of a star increases with each generation of stars, which means the older stars will be more metal-poor. This can be used as a clock but does not depend only time, but also on where the star formed, in higher density or lower density regions. Also, the metallicity of the next generation of stars can be affected by infall or outflow gas.

The chemical enrichment of the Universe as a whole is highly inhomogeneous. The chemical enrichment in the more luminous (and hence more massive) galaxies is generally faster, and more efficient than in the fainter galaxies (e.g. Tremonti et al. 2004; Lee et al. 2006; Simon & Geha 2007; McConnachie 2012). Not only the overall metallicities, but also the more detailed abundance patterns and chemical element ratios are highly dependent on the chemical evolution history of the system

A short overview is given of the main element groups that are commonly measured in stellar spectra. Figure 1.3 presents a periodic table indicating the different groups of elements.

- ***The Carbon Nitrogen Oxygen (CNO)-cycle:*** Carbon and Oxygen is mostly produced through the fusion of α particles. The reason these three elements are discussed together is that they are all used as catalysts in the H-burning phase of massive stars. In the process of turning H into He the abundances of C and (to a much lesser extend) O decreased while N is produced. Also the isotope ratio of C changes. Because H-burning happens deep inside a star, the results are not directly visible since we can only measure the chemical composition in the outer layers of the star. For the results of the CNO-cycle to become apparent we have to wait until the elements from the interior are brought to the surface by mixing processes. This process generally only significantly changes the C and N abundances. When brought to the surface these elements can also be released in stellar winds.

- ***α-elements:*** The α-elements, such as Mg, Si, Ca, Ti, are made out of α-particles (He-nuclei) during the various burning stages of heavier elements in massive stars and they are blow out into the interstellar medium by SN II explosions, which mark the end of massive stars that explode $\sim 10^7$ yr after their formation. Also the element Na and Al are mostly created and dispersed in SN II,

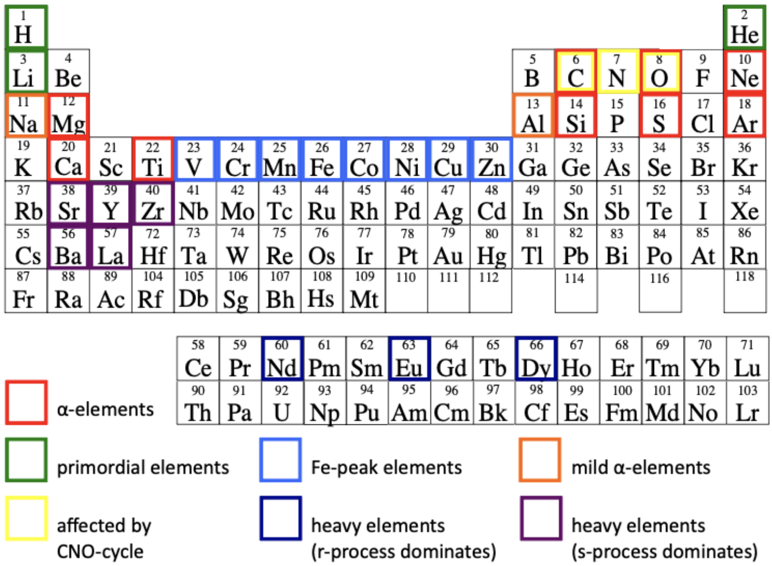


Figure 1.3 – *The periodic of table of chemical elements for astronomers indicating different kinds of elements, in which the processes responsible for their origin are color-coded. Figure from Starkenburg (2011).*

in the same way as α-elements, they are sometimes called “mild α-elements” (McWilliam 1997)

- ***Iron-peak elements:*** They are created, and expelled into the ISM during supernova explosions. Fe-peak elements are produced during SNe Type II explosions, but are predominantly produced and expelled into the ISM by SN Ia, supernovae thought to be due to mass transfer and the explosion of a white dwarf in an evolved binary with a less massive progenitor star, generally ~ 1 Gyr after the stars were formed.

- ***Neutron-capture elements:*** Nuclear fusion can create only elements up to Zinc, heavier elements are produced by neutron capture processes. These processes take place following two main paths: the slow and the rapid neutron capture processes (s- and r- process for short). For many elements there are two ways of producing them, using the r- and the s-process, but the isotope ratios will be strongly different. The s-process occurs in low and intermediate-mass stars at the end of their lives and in the Helium and Carbon burning phases of more massive stars. The neutron densities are relatively low and the time scales for n-capture are larger than typical decay times of unstable isotopes created, so it is called slow, while the rapid case occurs under opposite conditions. Heavier stable nuclei are built by adding neutrons to iron. The r-process happens in an environment with high neutron flux and neutron-capture takes place on timescales shorter than the decay time so that unstable isotopes can be produced before they decay. Observing the relative abundances of s- and r- process nuclei can therefore constrain the impact of AGB stars on the chemical evolution and probe star formation timescales. Observational evidence, showing high abundances of the lighter n-capture elements (such as Sr, Y and Zr) as compared to the heavier capture elements (such as Ba and Eu), has suggested the need for a special weak neutron-capture process, which primarily creates the lighter elements (François et al. 2007).

1.5.2 Abundance Ratios

It has long been recognized (Tinsley 1979; Matteucci & Greggio 1986) that the element abundance ratio [α/Fe] is a powerful estimator of the duration of star formation events in galaxies. This is because of the different explosion timescales and yields of different types of supernovae.

Elemental ratios of the type [α/Fe] inform us of the relative contribution from the two types of supernovae at a given time, indicative of star formation timescales. When the star formation rate (SFR) is high, then the gas will reach higher [Fe/H] before the first SN Ia occurs . The downward turn of the [α/Fe] vs. [Fe/H] trend seen in the resolved MW data is known as a "knee" and is an indication of the metal enrichment achieved up to that point in time. For instance, a lower [Fe/H] at the knee location means lower feedback from star formation. The formation efficiency and time scale of a stellar system can be estimated from the position of this "knee". Because more massive stars are more efficient in producing α-elements, at low metallicity the level of α/Fe can be used as indicator of the mass of the stars which contributed to the enrichment the ISM and so provides a indirect measure of the IMF. Figure 1.4 shows how α-elements can be used to trace the IMF and SFH of a galaxy.

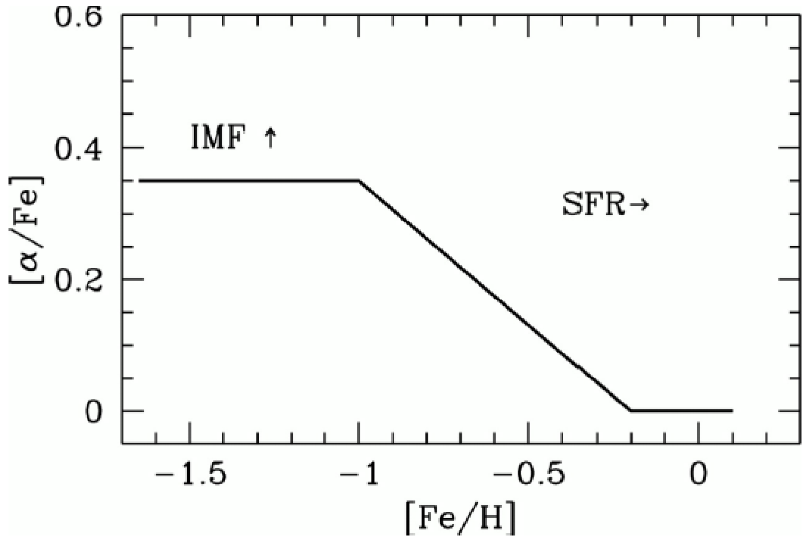


Figure 1.4 – *A schematic diagram of the trend of alpha-element abundance with metallicity. Increased IMF and SFR affect the trend in the directions indicated.*

In the MilkyWay, a typical metal-poor halo star shows abundance ratios [α/Fe] $+0.4$ (e.g., McWilliam 1997). Thick-disk stars have relatively higher abundance ratios ([α/Fe] $+0.3$ to $+0.4$; Bensby et al. 2003, 2005; Reddy et al. 2006) than thin-disk stars ([α/Fe] 0.0 to $+0.1$). Many stars in the dwarf spheroidal galaxies (dSphs) near the Milky Way have relatively lower [α/Fe] than the Galactic halo stars of the same metallicity for [Fe/H] $>$ -2.5 (Shetrone et al. 2001, 2003; Fulbright 2002; Tolstoy et al. 2009).

Gorgas et al. (1997) made the first [α/Fe] measurement for a dE outside the Local Group, in the Virgo cluster. They suggest that Virgo dEs are consistent with solar [α/Fe] abundance ratios, showing a more gradual buildup of low-mass systems.

Abundances of various elements can be measured in stars of different ages and, due to their different nucleosynthetic origin, let us understand which enrichment processes have been dominant at different epochs of galaxy formation.

The formation and evolution of dEs is not known in great detail. The most straightforward way to learn about these processes is by studying the present-day properties of these galaxies and their stellar populations. Studying elemental abundances in dwarfs gives us a chance to learn about the origin of dEs.

1.6 Stellar Populations

For unresolved stellar systems stellar population synthesis is the main technique required to understand their formation and evolution. Through quantitative analysis of the stellar content of galaxies one has been able to obtain information about physical quantities such as stellar masses, chemical abundances and star formation rates, and to look back in time on the evolution and chemical enrichment history of galaxies. Stellar population studies have followed two methods. First, in nearby galaxies the properties of individual stars can be studied through a detailed comparison between theory and observations; this way has allowed us to have knowledge of the star formation history of the Milky Way and nearby Local Group galaxies. Unlike most galaxies in the Local Group, more distant galaxies cannot be resolved into individual stars, so that the nature of all galaxies, from about 15 Mpc until the highest redshifts, has to be obtained from their unresolved stellar populations.

1.6.1 Resolved Stellar Population

Baade was the first to observe individual stars in M31 and M32 and to classify stars into several populations back in the 1940's. This work was a milestone for stellar population studies. The study of individual stars is the direct way to understand their nature. An efficient way to learn about the stellar populations of galaxies is the color-magnitude diagram (CMD). The location of any star on the CMD is depending on its mass, age and metallicity. The SFH of galaxies can be estimated using main sequence turn off points, position and width of the red giant branch, and the presence of asymptotic giant branch stars (see for Gaia HRD in Fig. 1.5). The main sequence turn off point is the best age indicator of galaxies, hereby linking the age of the galaxy to the luminosity and mass of the turnoff, while the red giant branch is more sensitive to the metallicity of the sytems. Star formation histories of galaxies can be determined by fitting models based on stellar evolutionary tracks to CMDs.

After the launch of the Hubble Space Telescope, the number of resolved galaxies increased. However, even with HST one can only resolve galax-

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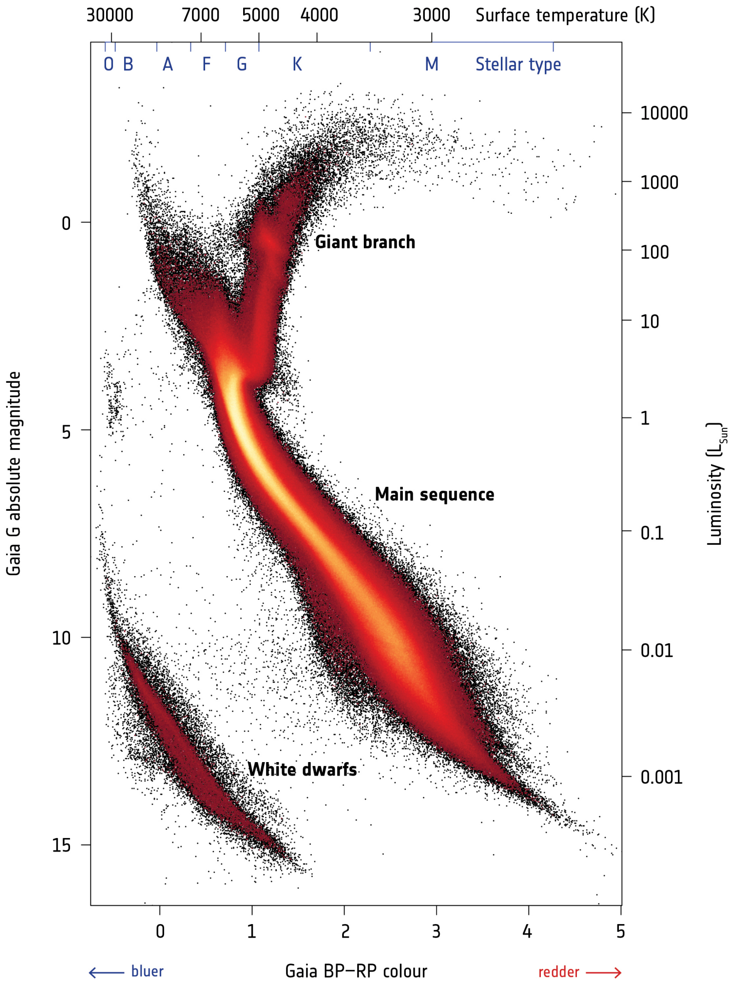

Figure 1.5 – *Gaia HRD of sources with low extinction ($E(B - V) <$ 0.015 mag) satisfying the filters described in Gaia Collaboration et al. 2018 (4,276,690 stars). The colour scale represents the square root of the density of stars. From Gaia Collaboration et al. (2018).*

ies up to the Virgo cluster, where the brightest stars can be resolved. The situation with JWST will not be much better than HST, since this telescope, although having a larger diameter, will observe in the red and infrared. There is hope, however, from ground-based telescopes,where diffraction-limited imaging can be reached using adaptive optics. With the upcoming E-ELT, with a diameter of 40m, galaxies up to about 100 Mpc will be resolved.

1.6.2 Unresolved Stellar Population

A galaxy spectrum is very powerful because it provides large amount of information on its properties such as mass, chemical composition and star formation history. The analysis of the spectral energy distribution (SED) of a galaxy allows us to look back and relate the mechanisms involved in the formation and evolution to its intrinsic properties or the environment in which it was born.

When stars are not resolved, we can use photometric or spectroscopic observations of integrated magnitudes, colors and spectra to research the stellar population. The photometric method is about measuring broad-band colors and comparing them with the colors of model populations, while the spectroscopic method relies on the measurement of absorption line-strengths representing relevant spectral features or on full spectral fitting. In the following we will explain the method using absorption line indices, which is the main technique used in this thesis.

In general, the only means available to study the stellar populations of elliptical galaxies studies is their spectral energy distribution (SED) which contains light from all their stars, having a range of metallicities and ages. Single Stellar Populations (SSP), representing a generation of coeval stars, are used to interpret the integrated light of galaxies and estimate their ages and metallicities. This method was introduced in the pioneering work by Tinsley (1972) is still commonly in use and is defined as

$$f_{SSP}(t, Z) = \int_{m_l}^{m_u(t)} f_{star}(t, Z, m)\Phi(m)\mathrm{d}m, \tag{1.1}$$

where, $f_{star}(t, Z, m)$ is the flux emitted by a star of mass m , metallicity Z and age t , which is integrated between a lower m_l and upper $m_u(t)$ mass, and $\Phi(m)$ is the IMF. m_l is also time-dependent, but only weakly so.

The general approach is to study the unresolved light coming from the contribution of the different populations to the integrated spectra. This can be predicted using the population synthesis models. All methods dealing with unresolved stellar populations are based on comparison of observations and models: empirical or theoretical. These models can be either based on purely theoretical stellar spectra (e.g. Schiavon & Faber 2000; Coelho et al. 2007) or from empirical data of a well-defined sample of stars (e.g. Peletier 1989; Vazdekis 1999; Bruzual & Charlot 2003; Vazdekis et al. 2003; Maraston 2005; (Schiavon 2007); Conroy, Gunn & White 2009; Conroy & Gunn 2010; Vazdekis et al. 2010; Maraston & Stromback 2011; Conroy & van Dokkum 2012a). The most often used large spectral libraries of stars, covering a considerable range of atmospheric parameters, are ELODIE (Prugniel & Soubiran, 2001) and MILES (Sanchez-Blazquez et al., 2006c).

The study of Worthey et al. (1994) presented one of the most detailed early analyses of galaxy spectra, defining a set of indices (Lick indices) measuring the strength of optical features, and applying evolutionary synthesis to these. Grids of models for a wide set of ages and metallicities are studied. It was shown that exploiting different sets of indices gave a possibility to break the effects of age and metallicity.

Defining both an age and a metallicity of a galaxy, or even of an SSP, is harder than it looks. Galaxy colors become redder as the galaxy ages because more stars move to the giant branch, and also for increasing metallicities, since the effective temperatures of most stars decrease because of increasing opacities in the stellar photosphere. Population synthesis models often show the presence of a degeneracy between age and metallicity, i.e. that one cannot find out whether a red colour alone is due to old stars or to high metallicity. It is difficult to overcome this degeneracy with the models alone. However, there are ways to break the degeneracy. For spectra covering only a small range in wavelength, very sophisticated indices have been developed maximizing age-sensitivity while minimizing the sensitivity to metallicity (e.g. Vazdekis & Arimoto 1999).

The aim of the line-strength technique is to measure individual absorption features which are sensitive to one or more parameters of the integrated stellar population (e.g. age, metallicity, elemental abundances, IMF slope). These measurements are applied on a narrow range of a spectrum in which a feature with a width of a few Å is centered on a particular absorption line. The index, labeled as i, expressed in Å, is usually defined as

$$I_i = \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{F_{I,\lambda}}{F_{C,\lambda}}\right) \mathrm{d}\lambda, \tag{1.2}$$

where $F_{I,\lambda}$ represents the measured flux over the feature in the wavelength range from λ_1 to λ_2, and $F_{C,\lambda}$ represents the straight line connecting the mid-points of the side-band pseudo-continuum fluxes (e.g. Worthey 1994).

Some indices are defined in a logarithmic way. These so-called molecular features have the following definition:

$$I_i = -2.5 \log \left[\left(\frac{1}{\lambda_1 - \lambda_2} \right) \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{F_{I,\lambda}}{F_{C,\lambda}}\right) \mathrm{d}\lambda \right]. \tag{1.3}$$

1.7 This Thesis

In this Ph.D thesis, we define the physical properties of dEs by focusing on their elemental abundances and stellar populations as analysed using integral field unit and long-slit spectroscopy. The aim of this work is to help a better and more complete understanding of star formation histories of dwarf ellipticals using abundance ratios. For local group galaxies, this method has been shown to be very powerful (see e.g. Tolstoy et al. 2009). For example, the [α/Fe] ratio can show whether star formation has been fast (like in our halo) or slow, as is the case in the disk. Abundance ratios of other elements can give more details of the IMF of the stars responsible for the chemical enrichment of the galaxy, and the interaction history.

Chemical abundances provide us with information about the stellar populations. Stellar population studies show that dEs have on average younger ages and a lower metal content as expected from the metallicity luminosity relation (Michielsen et al. 2008; Skillman et al. 1989). However, recent studies show that stellar populations in dEs show indications of both young and old ages and varied gradients (e.g. Koleva et al. (2009, 2011); Ryś & Falcón-Barroso (2012)). But these results lead to a lot of open questions. What are their star formation histories? Do dwarf ellipticals always contain an underlying old population, with a relatively small fraction of more recently formed stars? What are the scaling relations for dwarf galaxies, such as index - index and line strength - stellar mass relations?

We investigate the open questions of the dwarf galaxy evolution using spectral analysis obtained using by long-slit and IFU. These data allow us to obtain abundance ratios for a number of elements which have never been studied before for dEs outside the Local Group.

We determine abundance ratios of 37 dEs in the Virgo cluster. We present their ages, metallicity and abundance ratios for Na, Mg and Ca. We discuss their possible formation relations (Chapter 2). For various elements we want to investigate in detail their elemental abundance, so we need to high-resolution spectral indices. We define a new set of high-resolution indices, analogous to the Lick indices and investigate the dependence of the line indices on alpha enhancement (Chapter 3). We perform a detailed stellar population of 8 dEs in Fornax cluster using the newly defined line indices of Chapter 3 and measured their abundance ratios (Chapter 4). In Chapter 5, we present a general overview of our results, conclusions based on the previous chapters, and discuss of the future prospects.